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Electric Propulsion for Spacecraft: An Assessment Technologies for Spacecraft

Thomas Coleman[1] *

[1]Cobden High School, Cobden, IL, USA
*Corresponding Author: tbcoleman1007@gmail.com

Advisor: German Saltar-Rivera, germans3@illinois.edu

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Abstract

Electric propulsion refers to a type of propulsion system that uses electrically charged particles instead of chemicals or fuels to generate thrust. Electric propulsion is important because it offers several advantages to the common chemical and gas thrusters we use today, such as increased efficiency, better fuel consumption, longevity, and performance measurements. The issue this paper addresses is the complex decision of which electric propulsion system serves the best benefit in replacing cold and warm gas propulsion systems. Each system was weighed in the categories of complexity, cost, engine life, efficiency, thrust, and specific impulse (Isp). Environmental impacts are also considered. These six categories were chosen because they are often the most important factors in their implementation on spacecraft. The results show overall electric propulsion outperforms gas propulsion systems in the many categories of range in specific impulse, engine life, efficiency, and thrust with Gridded Ion Engines providing the highest mean specific impulse and resistojets providing the highest probable thrust densities. Cold and warm gas propulsion systems reigned in the categories of cost and complexity due to their simple design, manufacturing, and implementation.

Keywords: Electric propulsion, Cold/Warm gas propulsion, Resistojet, Magnetoplasmadynamic, Gridded ion engine, Hall effect thruster, Cusped field thruster

1. Introduction

The use of chemical rockets as well as cold and warm gas propulsion systems for space travel is truly a revolutionary development. These systems have been used numerous times for space exploration and have been deemed quite successful. However, the applications of these propulsion systems have revealed a variety of issues regarding their use. Examples include low-efficiency levels, low specific impulse, and even environmental impacts when tested within the atmosphere. These issues have given rise to the development of electric propulsion (EP) systems. EP systems have shown great potential benefits and advantages when compared to the other commonly used thruster systems. EP systems have given results such as high specific impulse, high-efficiency percentages, little complexity, high engine life, compatibility with multiple propellants, and high achievable amounts of thrust. Recent advancements in electric propulsion technology have led to the introduction of several relatively new thruster systems. These include electrothermal propulsion systems such as resistojets, electromagnetic propulsion systems like the magnetoplasmadynamic (MPD) thruster, and electrostatic propulsion systems, which encompass the Gridded Ion Engine (GIE), Hall Effect Thruster (HET), and Cusped Field Thruster (CFT), according to Yeo et al. (2021).

Previous studies have demonstrated that the EP systems discussed above possess both similarities and differences and offer various advantages and disadvantages regarding their implementation and in replacing traditional combustion rockets and cold/warm gas systems. However, there are gaps in the comparison between these systems such as measurements of thrust, range, power density, safety, complexity, etc. It is difficult to quantify these factors and bring a comparison between all of these systems. The objective of this study is to review research done by professionals in the aerospace field to provide a concise understanding of these types of propulsion and to quantify their advantages and disadvantages in the categories of complexity, cost, range in specific impulse, engine life, efficiency, and thrust. I found that these categories are representative of the important considerations when implementing these specific EP systems in spacecraft. Researching these specific categories can provide a quality answer to which system holds the best factors for spacecraft implementation.

1.1 Cold & Warm Gas Propulsion

For us to have a concise understanding of the benefits and disadvantages of these different types of EP systems, we should understand conventional propulsion systems such as cold gas and warm gas propulsion. To generate thrust, these systems accelerate a cold or moderately heated gas through a nozzle. The propellant is allowed to flow from a propellant storage tank to a converging/diverging nozzle expanding to open space, seen in Figure 1 (Zaberchik et al., 2019). Propellant storage tanks, along with any necessary fluidics components like flow control valves are also included (Martínez & Lafleur, 2023). The feed system includes a pressure differential –a component that creates a pressure difference– from the pressurized tank between the propellant tanks and the nozzle. The required power is used to control valves and sustain temperature to maintain the propellant's minimum temperature before being expelled from the nozzle (Lemmer, 2017). Figure 1 depicts a simple system schematic of a cold/warm gas thruster and includes the propellant tank, valves, regulators or plenums, and the diverging nozzle used to accelerate the gasses. As we can see, cold/warm gas thruster propellants typically take a simple route to being expelled from the propulsion system. Xenon, butane, liquid sulfur hexafluoride, nitrogen, argon, R134a, and R236fa are commonly used propellants (Lemmer, 2017). Other fuels include krypton, helium, dry air, ammonia, and iodine (Martínez & Lafleur, 2023). Interestingly, with such an array of usable propellants, other common compounds are being considered such as water. It can be stored in a liquid state and then vaporized to produce thrust. Moreover, many of these listed propellants have been used in numerous space missions. As examples, nitrogen was used in the NASA ST5 and Orbcomm missions, and xenon was used on the MEPSI and PROCYON missions (Martínez & Lafleur, 2023).

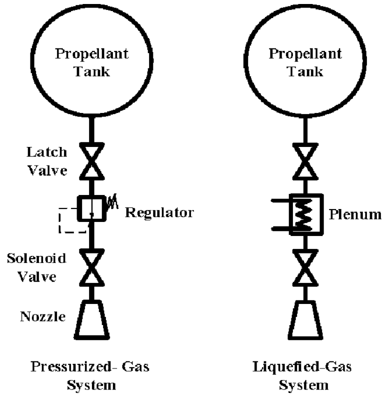


Figure 1: Simple system schematic of cold and warm gas propulsion with labels (Mishra & Mohite, 2020).

MEPSI, stands for MEMS Picosat Inspector. It was a CubeSat that implemented the use of a cold gas thruster named "MiPS", which stands for Micro-Propulsion System and was produced by VACCO Industries. MiPS is extremely flexible and can be used on a wide range of spacecraft. On MEPSI, MiPS provided formation flying, altitude control, and velocity change (Cardin et al., 2003). MiPS was specifically chosen for the MEPSI mission because of its total impulse capacity, which is the sum of measured thrust values multiplied by time increment, of 34 N-sec over five thrusters, two softseat valves that prevented storage tank leakage, self-pressurization for the propellant, and a compact, robust design made of titanium and also served as a storage tank (Cardin et al., 2003). MiPS is one of the most capable and versatile propulsion systems for the MEPSI spacecraft by providing it with 34 N-sec of total impulse and up to 62,000 minimum impulse bit firings (Cardin et al., 2003).

Cold gas and warm gas propulsion systems have a low specific impulse of tens to hundreds of seconds, depending on the propellant's atomic mass (Zaberchik et al., 2019). As seen in Figure 7a, cold and warm gas propulsion can provide thrust density in the range of 0mN to upwards of 100mN depending on the propellant. Additionally, testing done by Arestie et al. shows a cold gas propulsion system developed at the University of Texas at Austin's Satellite Design Lab measured a specific impulse that ranged from 65 seconds at 24ºC to over 89 seconds at 85ºC (2012). Also, the system's measured thrust ranged from 110mN at 24℃ to 150mN at 85ºC. Based on these findings, cold and warm gas propulsion systems' measurements can range in specific impulse and thruster depending on their applied temperature (Arestie et al., 2012).

1.2 Resistojet

A resistojet thruster is an electrothermal EP system, meaning it electrically heats a propellant that produces thrust. Resistojets use a heating element to increase the temperature of the thruster, ionizing the chosen propellant, and producing thrust from the nozzle section as shown in Figure 2. These propulsion systems are widely used for spacecraft, more specifically satellites, control, tangential orbit modification, and general propulsion services (Aswin et al., 2024). The performance of a resistojet is highly reliant on the design of the system. Along with system design, the propellant chosen plays a crucial role in the performance aspects of a resistojet. Resistojets and other electrothermal propulsion systems are quite similar to warm and cold gas propulsion. Although such electric propulsion systems share many similarities with cold and warm gas thrusters, their typical operating conditions are chosen so that heating with an electrical element, or through plasma-gas collisions, are the main drivers of thruster performance (Martínez & Lafleur, 2023). Figure 2 shows a simplistic design of a resistojet thruster that, when compared to Figure 1, shows the similarities of cold/warm gas systems and resistojets but with a main difference of electrical heating.

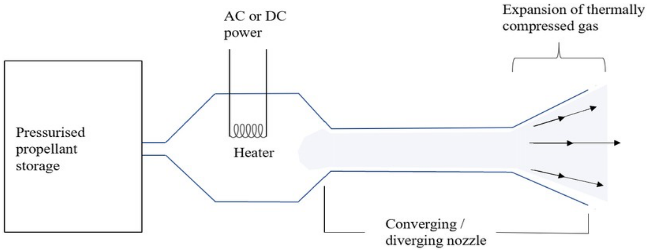


Figure 2: System schematic of resistojet propulsion system with labels (O'Reilly et al., 2021).

For real-life analysis, a resistojet engine was used on the Intelsat-V spacecraft. This thruster used hydrazine as a propellant. This system used a decomposition heater, which broke down the hydrazine into nitrogen gas, hydrogen gas, and ammonia (Vaughan et al., 1992). The thruster also contained a tungsten filament used to superheat the gases. This thruster worked on a power requirement of 5W and produced 295 seconds of Isp. However, this was still early being in the late 1970s and the resistojet underwent heating failures and was deposed by nonvolatile residue (Vaughan et al., 1992).

1.3 Magnetoplasmadynamic Thruster

The magnetoplasmadynamic (MPD) thruster is a form of electromagnetic propulsion. Electromagnetic propulsion utilizes magnetic fields and electrical currents to produce thrust. The MPD thruster works on the concept of the Lorentz Force. The Lorentz Force refers to the effects of the magnetic field resulting from the flow of current through a loop. The current through the conductors causes a magnetic field below and the interaction between the flowing electric charges in the rod and the magnetic field produces a force on the rod that causes it to accelerate away from the current source as shown in Figure 3 (Sarathkumar et al., 2012). Figure 3 illustrates the direction in which the propellant goes and the interactions between the propellant, anode, cathode, and the movement of the propellant due to the Lorentz Force.

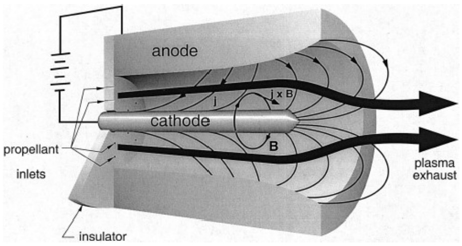


Figure 3: Simple system schematic of a magnetoplasmadynamic thruster with labels (Lev, 2012).

MPD thrusters can operate steady-state for hours or quasi-steady –meaning entering energy and exiting energy are equal–, pulsed for 1-10 ms at a frequency determined by spacecraft power (Myers, 1993). Michael R. LaPointe et al. (2004) describe how an MPD thruster's specific impulse can be adjusted to suit specific mission requirements, ranging from a few thousand seconds with heavier gas propellants to 10,000 seconds with hydrogen propellants. Typically, MPD thrusters can provide small impulse bits for satellite positioning, high specific impulse, robustness, high power processing capability, and system simplicity. MPD thrusters offer numerous benefits, but their low efficiency and limited lifetime have limited their use in actual missions (Myers, 1993). Electromagnetic MPD thrusters have demonstrated the ability to process megawatts of electrical power at the laboratory level, offering significantly higher thrust densities than electrostatic electric propulsion systems (LaPointe et al., 2004).

A system like this was used on the Japanese Space Flyer Unit (SFU), which launched in March 1995 and returned in January 1996. The propulsive function of the MPD thruster was verified after successfully firing over 40,000 shots during a few days of the experiment, aligning with the results of ground testing (Toki et al., n.d.). After the flight, hydrazine fuel was successfully disposed of, and no abnormal discharges were reported. In this mission, the MPD thruster was composed of a cathode with a 10-millimeter diameter, 8 segmented anodes for the production of a self-induced magnetic field, and a nozzle made of boron nitride providing aerodynamic thrust. On this mission, the thruster performed at an Isp of 1,100 seconds over the span of 43,395 pulses during orbit (Toki et al., n.d.).

1.4 Gridded Ion Engine

Gridded Ion Engines are another example of EP systems and have been in development since the 1960s. GIEs are electrostatic, in that they create an electric field that accelerates ions producing thrust. They are commonly used for altitude and trajectory control for geostationary communication satellites and interplanetary missions (Yeo et al., 2021). GIEs have three major components and those are the plasma generator, ion accelerator, and electron neutralizer (Yeo et al., 2021). In the exit, or discharge chamber, of the plasma generator, a gas propellant is ionized via a radio frequency, direct electrical current, or microwave discharge. This ionized gas then produces thrust. The ions are then accelerated by charge grids in the ion accelerator. Finally, at the neutralizer, the cathode, as seen in Figure 4, provides electrons that neutralize the exiting ions (Yeo et al., 2021). Figure 4 provides insight on the inner workings of GIEs by showing the process a propellant undergoes once it is injected to propel the spacecraft system.

Since their flight tests in the 1960s, ion thrusters have played important roles in the propulsion of many spacecraft. Ion optics, as a crucial component of the engines, have evolved in many aspects intending to increase the thruster's service life (Sangregorio et al., 2018). Gridded Ion Engines can produce high specific impulses. GIEs offer very attractive specific impulses, in the range of 1500-4000 seconds, with exhaust velocities up to about 100km/s for typical designs. Also, GIEs typically operate at powers from 1-40kW and thrust the 10-1000mN range (“Dual-stage”, 2006).

A Dual Stage 4 Gridded Ion Engine (DS4G) was used in 2008 as part of the HiPER project in Europe. This system was composed of 4 grids. The first, was a screen grid containing holes with about 1 millimeter radius. The second, was the extraction grid. The holes in this grid are smaller than the first grid at about 0.7 millimeters, but is four times the thickness of grid 1. The third grid, known as the accelerating grid, is nearly identical to grid 2. Lastly, the fourth grid, the earth grid, had the function of limiting downstream erosion (Coletti et al., n.d). Typically, there are not 4 grids in a GIE due to the complexity imposed by adding a fourth. After testing, the DS4G was compared to a traditional GIE thruster. With both having the same power input at 25kW, the DS4G had 0.1N thruster less than the traditional GIE thruster with a measurement of 0.45 compared to 0.46. However, the DS4G had a larger amount of Isp at 10,000s compared to the other GIE at 8270s (Coletti et al., n.d).

1.5 Hall Effect Thruster

Hall Effect Thrusters are another form of electrostatic propulsion. Like GIEs, HETs are considered the most favorable candidate systems for station keeping for satellite or deep space exploration missions (Yeo et al., 2021). For decades, the Hall Effect Thruster technology has been one of the most popular options for space propulsion systems. HETs are quite similar to ion thruster systems. Their major similarities are the use of xenon as propellants and hollow cathodes as seen when comparing Figure 4 and Figure 5 (Hofer et al., 2006). Figure 5 shows the process a propellant undergoes when it’s injected into the HET system and the factors that take place to produce a thrust.

At constant power, HETs generally have lower specific impulse, efficiency, and total lifetime than ion thrusters, but have higher thrust-power ratios. HETs often range within 1000 to 3000 seconds of specific impulse and can produce some of the most powerful thrusts of all EP systems (Hofer et al., 2006).

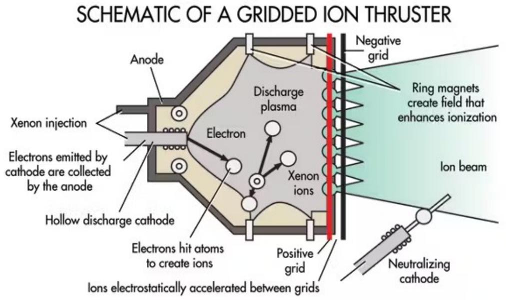


Figure 4: Simple system schematic of a Gridded Ion Engine with labels (“NASA”, 2013).

In the 1960s, the Soviet Union developed two types, namely the Stationary Plasma Thruster and the Thruster with Anode Layer. An extended acceleration region characterizes the Stationary Plasma Thruster type schematically and uses a dielectric channel wall to reduce wall erosion in the discharge chamber. The dielectric wall is defined by its high electric resistivities, which is what complements reduced wall erosion. Differently, the Thruster with Anode Layer uses a metallic channel wall (Yeo et al., 2021). The University of Michigan, along with the Air Force Research Laboratory and NASA, introduced a variant of the HET with a multi-channel nested configuration. This system can operate at power levels exceeding 100kW and features a neutralizer placed in the center of the thruster along with multi-discharge channels (Yeo et al., 2021).

Additionally, an HET was used in the SMART-1 mission. The SMART-1 spacecraft undertook a mission to the moon, during this mission the Hall Thruster was used in the electric propulsion subsystem for orbit. An orbit was achieved by the thruster system and proved the ability for HETs to perform highly sensitive orbiting maneuvers (Koppel & Estublier, 2005). This thruster accumulated nearly 5000 hours of in-space operation and performed at high specific impulses of 1600s and produced a thruster of 70mN, requiring a power output range of 650 – 1420 W with a xenon propellant (Williams, 2022).

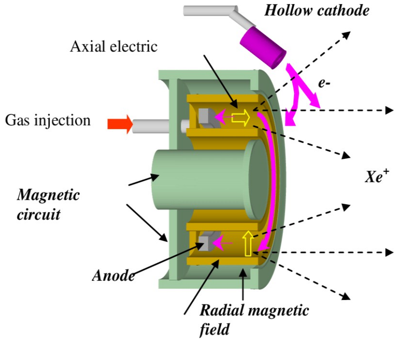


Figure 5: Simple system schematic of a Hall Effect Thruster with labels (Dudeck et al., 2012).

1.6 Cusped Field Thruster

The CFT is quite similar in design to the HET but offers greater performance measurements in specific impulses. Xenon is one of the most favorable propellants for CFTs (Yeo et al., 2021). The main difference between CFT and HET lies in the magnetic field configuration. The CFT’s discharge channel is enclosed by a set of annular permanent magnets with pairwise opposite polarity shown in Figure 6, which simply means the magnets are adjacent with opposite polarities. This creates a magnetic field that is mostly parallel to the dielectric wall in most channels and also contains a magnetic cusp which comes from magnet interface orientation (Yeo et al., 2021). The magnetic cusp plays a crucial role in managing the interaction between the plasma and the device walls, which enhances performance and durability. Moreover, the magnetic field is strong near the channel walls in the cusp region, creating a strong magnetic gradient that becomes a “mirror,” reflecting charged electrons also shown in Figure 6, at the end point of each magnet (Yeo et al., 2021). The magnetic field of the CFT guides the electrons towards the wall, and then the mirror reflects them. Due to the mirror’s reflective ability, less wall erosion occurs. Figure 6 depicts the flow of electrons and their interactions with the magnets, wall, anode, cathode, and cusped field.

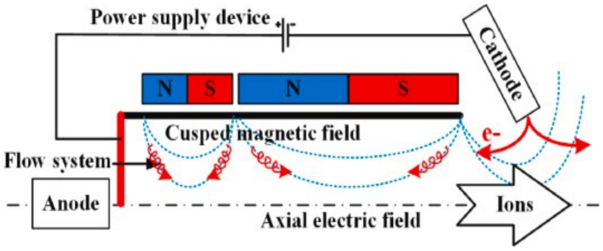


Figure 6: Simple system schematic of a Cusped Field Thruster with labels (Cui, 2021).

The Cusped Field Thruster was developed to produce a low-power plasma thruster with similar performance to typical HETs but with increased lifetime and specific impulse. As a promising candidate, the cusped field thruster has features such as a simple structure, high working stability, a long lifetime, and a low erosion rate (Cui et al., 2018). The cusped field thruster, with low noise and high resolution below 650W, can achieve continuously variable thrusts from 1 to 20mN, achieving 1800s specific impulses, and showing potential for drag-free flight. With further advancements, the CFT will provide more extensive implementation value (Liu et al., 2016).

A diverging Cusped Field Thruster was used on the CASTOR satellite developed by MIT. This thruster allows the satellite to make high efficiency orbital changes and maneuvers (Babuscia et al., 2012). The thruster was developed at MIT's Space Propulsion Laboratory. This system provides an orbital transfer platform with an exceptional performance to mass ratio. Because of this, launch costs are decreased. This system is mainly powered by the solar panels of the spacecraft but batteries can be used if additional power is needed. The anode of this system requires an input of 400 volts. The thruster used xenon as a propellant and performed an efficiency of approximately 43% with testing results indicating a thrust of 4.6 mN (Babuscia et al., 2012).

2. Methodology

2.1 Categories and Consideration

In this paper, six categories are considered to make an apt comparison between each of the propulsion systems above. These categories are complexity and cost, which are reviewed in the same subsections, engine life, efficiency, thrust, and specific impulse. I have evaluated these categories because I believe they are the main factors considered when implementing a propulsion system in spacecraft. The complexity subsections give insight into the system's implementation difficulty and the average cost of said system. Additionally, a propulsion system's longevity is always desired. The Engine Life subsections describe the range of useful lifetimes these systems can have as well as what impacts a system's lifespan.

Lack of efficiency is a prevalent issue in chemical propulsion systems. EP systems can provide substantial improvements in this category. The efficiency subsections attempt to quantify this, which is why Isp is considered in this review. Specific impulse is a way to help determine engine efficiency because it is the relation between the amount of thrust from an engine and the amount of propellant being used. Therefore, a higher specific impulse means more efficiency per unit of propellant used. Additionally, thrust and specific impulse are considered as these measurements directly relate to the performance capability of the thruster systems as a whole.

Environmental impact is also an imporant consideration for these technologies. In the Environmental Impact section, I have reviewed two main power sources for the EP systems reviewed in this paper, which are batteries and solar panels. In this subsections, the environmental impacts of manufacturing and disposal are considered for the two power sources. Additionally, emissions of these EP systems are reviewed to help determine the impact these systems truly have on our environment and atmosphere.

Finally, an overview of the advantages, disadvantages, and applications are overviewed in the Trade-offs section to provide a simple format to compare the six propulsion systems reviewed in this paper.

2.2 Statistical Analysis

To determine the probability density functions of thrust and specific impulse, python was used. A probability density function (PDF) is a fundamental statistical tool, that indicates the likelihood of a variable falling within a certain range, with a probability of 1. A PDF was used to create a visualization of the probability distribution of the variables of thrust and specific impulse for these propulsion types. By using a PDF, information was gained on the likelihood of different values occurring for these variables. The PDF provided an understanding of the range of possible measurements these systems can produce. The equation below was used to compute the probability function.

Firstly, the data's (x) range was divided into smaller ranges known as bins. The bin edges are defined as:

$$y_i = min(x) + i\Delta \tag{1}$$

where $i \in [0,\ N\ +1]$, $\Delta = \frac{\max(x) - \min\ (x)}{N_b}$ is the bin size and N_b is the number of bins. Then the number of input data points that fall within that bin is counted to create the histogram:

$$h_j = \sum_{x_k > y_j,\, x_k < y_{j+1}} 1 \tag{2}$$

where $j \in [0, N\ ]$ and $k \in [0, N]$ with N being the number of input data points in x. The probability density function is then computed as follows:

$$f_j = \frac{h_j}{\sum_j h_j} \tag{3}$$

To calculate the mean the equation used was

$$\mu = \frac{1}{N}\sum_k x_k \tag{4}$$

Lastly, the median was computed by arranging x inputs in ascending order and picking the middle value as the median. If there are two input values, then the average between those two was used.

Both mean and median will be considered for comparing the different EP systems. However, the mean is a more befitting comparison because it considers the overall performance measurements of each of these inputs.

2.3 Data Collection

Data was collected via literature review to acquire a general understanding of the types and inner workings of these propulsion systems. Additionally, during the literature review, there was an emphasis on the finding of graphs, charts, and testing reports that related to measured results in the six categories, with an emphasis on reported Isp and thrust measurements due to their use in the PDF analysis. To analyze the Isp, measurements were collected from the literature review data and then inserted into the function found in section 2.2. To analyze thrust, measurements were collected from the literature review data, converted to the same unit (mN), then inserted into the same function. Overall, there were two PDF functions used, one for Isp with the amount of measurement inputs ranging from 10 to 135, and one for thrust with the amount of measurement inputs ranging from 20 to 135.

3. Discussion of Results

3.1 Complexity & Cost

Cold/Warm Gas

Cold and warm gas propulsion are particularly simple in design, which makes them such an attractive choice. With this simplicity comes the added benefits of reduced costs when in design and low power requirements. Propellant selection for these systems is a particularly important factor since it influences thruster performance and determines propellant storage conditions (Martínez & Lafleur, 2023). Like the other systems in this research, cold/warm gas propulsion systems also offer a variety of propellants that can be used. Consequently, propellant storage systems are much more diverse and less complex. Propellants are evaluated for performance, storage requirements, density, mission suitability, and cost. Some require high-pressure storage, which can increase explosion risks, as high-pressure tanks can be hazardous (Martínez & Lafleur, 2023). Propellants stored as gas or supercritical fluids don't require subsystems, but electrical heaters can moderate gas stagnation temperature, increase thruster performance, and prevent condensation, with additional heaters used for enhanced performance (Martínez & Lafleur, 2023).

In comparison, these propulsion systems are much less complex than EP systems due to their easy design and mechanisms. Being less complex provides cost reductions and less power. However, having less cost doesn’t mean cheap because even low end propulsion systems for CubeSats can range from \$50,000 to \$200,000 (Pilcher, 2021). But, with such a dynamic and simplistic design, cold and warm gas propulsion systems make it easy to develop and launch small satellites used for many objectives (Martínez & Lafleur, 2023).

Resistojet

Resistojets are said to be one of the least complex forms of electrothermal propulsion. Characteristics of a resistojet are multi-propellant capability, the ability to operate at low thrust with a thrust-to-power ratio less than 0.2, a large operation range, the capability to trade performance for a lifetime, a small volume and mass, simple design and interfaces, great fuel economy and the ability to achieve specific impulse upwards of 1000s (Mirtich, 1982). Many are being developed to easily integrate with GIE and HET propulsion systems. Resistojets can comply with standard low-pressure EP systems, creating the potential for implementation downstream of the main pressure regulation stage without additional pressure regulators (Cifali et al., 2017). Resistojets are characterized by their capability to use multiple propellants, including H, NH_3, Xe, H_2O, CO_2, and even by-products of biowaste systems have been considered (Aswin et al., 2024). However, the implementation complexity of resistojets requires additional propellant tanks due to compatibility with fuels, which depends on the chosen propellant. Like mentioned above, resistojets are quite similar in design with cold and warm gas propulsion systems. Because of this, they are quite similar in cost as well and can range from tens of thousands of dollars to even hundreds of thousands or dollars, but generally fall in the range of $50,000 to $200,000 depending on the parameters set for the system.

Overall, in terms of complexity, resistojets can have low volume and mass, which allows easy implementation with or without GIE and HET systems. The multi-propellant capability of these EP systems allows them to have advantageous versatility.

Magnetoplasmadynamic Thruster

The major issues currently preventing the application of MPD thrusters to primary propulsion applications are low thruster efficiency, available spacecraft power, and spacecraft integration. However, the actual design of the MPD thruster system has the benefit of being quite simple. Also, concerning implementation, MPD thrusters can generate higher thrust densities, reducing the number of thrusters needed for a mission and reducing system complexity associated with multiple thruster arrays (LaPointe et al., 2004). MPD thrusters can provide one of the highest thrust densities processing input powers ranging from tens of kilowatts to some megawatts. In some cases, the application of a magnetic field has been found to increase thruster performance (Coletti, 2012). If this addition were to be implemented it would add to the complexity of the system. While the use of MPD thrusters seems quite promising for spacecraft implementation, author Roger M. Myers (1993) illustrates for MPD thrusters to compete with alternative electric propulsion technologies effectively, it requires significant improvements in capacitor and valve technologies. Additionally, it is hard to completely determine the cost of an MPD thruster considering the scarceness of their use, however, considering the amount of necessary power to run these systems the cost of an MPD thruster can be approximated from tens of thousands to maybe even millions per unit. While MPD systems may be quite simple, there are needed improvements in the overall technology to make MPD applications feasible. In terms of implementation, MPD systems lack in this category compared to the other propulsion systems in this study (Myers, 1993).

Gridded Ion Engine

GIEs along with HETs have been mounted on approximately 70% of all GEO satellites. GIEs are considered one of the most favorable candidate systems for station keeping for satellite or deep space exploration missions (Yeo et al., 2021). The extraction system of each GIE is specifically designed and built according to the propellant and the specific needs of the thruster (Sangregorio et al., 2018). While the application of GIEs seems common, there are multiple reasons why GIEs would not be implemented in place of other propulsion systems. These reasons are launch problems, operation issues, and sputter erosion, which are covered in section 3.2.

The development and cost to run such advanced spacecraft propulsion systems can have a large range of cost, especially due to the different parameters that are set for each mission where a thruster like this is used. The cost of GIEs are widely based on their specifications and intended application, but they generally range from several hundred thousand to a few million dollars for a complete system. Additionally, the use of xenon as a main propellant for ion systems imposed serious restraints for the use of these systems due to xenon's expensiveness, which is approximately $120 per 100 grams, and limited availability (Fazio et al., 2018).

Hall Effect Thruster

As stated above, HETs are mounted on approximately 70% of GEO satellites along with GIEs (Yeo et al., 2021). Additionally, all around the world, HETs are being widely adopted by nearly every major commercial satellite manufacturer (Hofer et al., 2006). Like all engines, HETs need to meet mission requirements and do so at low costs. In comparison to ion engines, HET systems are generally less complex than ion thruster systems, which can translate into mass and cost reductions (Oh et al., 2009). Many factors contribute to this simpler design of ion engines including only one cathode, lower parts count, and lower operating voltage. Moreover, HETs sharing xenon as a propellant with ion systems allows the potential shared use of fuel tanks and other feed systems (Hofer et al., 2006). However, HETs have some performance flaws that limit their implementation to spacecraft. These flaws are wall loss and immense power requirements, but there have been significant developments such as magnetic shielding to reduce wall loss and the introduction of permanent magnets to reduce power requirements for the magnetic circuit (Yeo et al., 2021).

Like the other systems in this paper, the cost of HETs can vary depending on the mission parameters and specifications. Smaller sized HETs are relatively inexpensive with a 200 Watt HET being developed at only $2100 (Baird et al., 2017). But while the smaller, research-grade models range in the thousands, larger thrusters used in space missions can increase in price to the tens of thousands of dollars.

Overall, Hall Effect Thrusters are quite simple in system design with relatively low costs. While there have been performance issues, there has been many significant developments to help make HETs a feasible application to spacecraft.

Cusped Field Thruster

As stated above, the Cusped Field Thrusters have similar technology to HET systems and are simpler regarding design aspects (Yeo et al., 2021). Additionally, CFTs are similar to HETs and GIEs in that their ionization processes take place upstream and acceleration of said ions takes place at the exit of the system as described by Hiu Liu et al. (2016) and seen in Figure 6. However, CFT's differentiate from HET's due to the fact the plasma within the system is confined from the wall. Along with this, CFTs are different from GIEs since they do not contain a grid for the ions at the exit point (Liu et al. 2016). Being an electrostatic propulsion device, CFTs can run on multiple propellants, but typically Xe.

While the CFT is simpler in design and less complex, when considering size, ideas clash in two studies: *Low Power Cusped Field Thruster Developed for the Space-Borne Gravitational Wave Detection Mission in China* (Liu et al., 2021) and *Design of a cusped field thruster for drag-free flight* (Liu et al., 2016). Author Liu et al., describes a decrease in size as nothing to fear regarding thrust levels and overheating in their 2016 study due to its limitlessness of space charge saturation, absence of excitation coils, and the confinement of plasma from the wall. However, the 2021 study done by Liu et al describes the size effect as inevitable in Cusped Field Thruster downscaling. Downscaling is shown to lead to problems such as difficulty in conduction and inefficiency in ionization leading to lowered performance results. This shows the scaling of CFT size is limited due to conduction and ionization constraints (Liu et al., 2021).

The cost of a CFT is hard to determine since they are still emerging technologies that have rarely been used in space missions. Small, research-grade CFTs, like many other propulsion systems, are smaller and can costs several thousand dollars. But, overall, with optimization in size and advancement in cusped technologies, CFTs are emerging as great potential in space flight and transportation due to a simplistic design (Liu et al., 2016).

3.2 Engine Life

Cold/Warm Gas

Cold and warm gas propulsion can have varying lifetimes like many propulsion devices. The propellant and design of the tank play a crucial role in the system's lifespan due to varying rates of erosion. However, cold/warm gas propulsion systems can run for extensive periods as seen in the "Strawman Mission" which ran on cold gas propulsion and had a 5-year mission lifetime (Cardin & Acosta, 2000).

Resistojet

The engine life of a resistojet system can vary. The lifespan can extend into thousands of hours, but that depends on multiple factors such as propellant choice, mission requirements, design, and maintenance practice. However, resistojets continually provide long hours of service; their ability to trade performance for longevity plays a crucial role in this service time (Aswin et al., 2024)

Magnetoplasmadynamic Thruster

MPD thrusters commonly have a shorter length of life. Studies have shown engine life of MPD thrusters is determined by the type of propellant used. Authors Maris A. Mantenieks and Myers performed testing of MPD systems (1993). The testing revealed severe erosion of the cathode and boron nitride insulator, which decreased significantly with reduced propellant contamination. The copper anode also experienced severe erosion due to propellant sputtering. This happened to mark the first observation of this phenomenon in MPD thrusters. This suggests that long-life MPD thrusters require light gas propellants like Hydrogen, deuterium (^{2}H), or Lithium (Mantenieks & Myers, 1993). As we can see, thruster life varies due to erosion rates with these systems. However, a choice of lighter elements or gas for a propellant can lead to longer engine life.

Gridded Ion Engine

GIEs have a very long life span in comparison to other electric propulsion methods. Ion optics, as a crucial component of the engines, have evolved in many aspects intending to increase the thruster's service life. The entire lifetime of GIEs can range from 10,000 to 100,000 hours (Van Noord, 2010).

There are numerous reasons as to why the engine life of GIEs can vary. Launch problems can generate plastic deformation, grid-to-grid contact, and aperture misalignment (Sangregorio et al., 2018). Thermal expansion results in buckling and plastic deformation, which prevents proper thruster operation (Sangregorio et al., 2018). GIEs also have operation issues and sputter erosion decreasing engine lifetime overall. Temperature difference induces thermal expansion that changes the size of the acceleration gap between the screen and accel grids, which will directly affect the ion trajectories and the perveance of the ion optics (Goebel & Katz, 2008).

Hall Effect Thruster

HETs have quite an extensive life. However, in comparison to other EP systems, especially GIEs, they have a limited life span. The typical operation time for an HET is approximately 10000 hours, but this can vary (“Chapter 7”, n.d.). Like many EP systems, the chosen propellant plays an impact on the lifetime of these thrusters. The type of propellant being used can cause erosion or reduction of the wall. But in comparison to cold and warm gas chemical propulsion, the HET is still a more viable option in regards to engine lifespan.

Cusped Field Thruster

Cusped field thrusters are developed with the intent of a long lifetime. While they are similar to HETs, they have lower erosion rates which leads to an overall increase in lifetime (Yeo et al., 2021). The CFT’s unique addition of a cusped magnetic field makes this possible (Liu et al., 2016). Additionally, since CFTs do not contain a grid, as stated in the above section, they are more capable of achieving a long lifetime compared to GIE systems. Moreover, reported maximum erosion rates were demonstrated by an MIT-designed CFT during an experimental procedure being far lower than low-powered HETs (Liu et al., 2016). Overall, the CFT propulsion system has a long lifetime in comparison to chemical propulsion and other EP systems.

3.3 Efficiency

Cold/Warm Gas

Cold and warm gas propulsion are known to have some of the lowest efficiency percentages, especially when compared to EP. As seen in Figure 7b, cold and warm gas propulsion provides some of the lowest measurements of specific impulse. From this information, we can infer that low measurements of specific impulse cold and warm gas propulsion provide lower efficiency percentages than any of the EP systems discussed in this paper.

Resistojet

Resistojets are often used for their efficiency. They are known for their outstanding fuel economy (Aswin et al., 2024). The efficiency percentage of a resistojet thruster can range and depends on multiple factors such as how the system was designed, the chosen propellant, nozzle diameter, and pressure. Typically, resistojets have a range of efficiency from 65% to 85%. In many cases, efficiency loss can happen through heat transfer or the dissociation of byproducts from the propellant. An increase in chamber pressure can be used to help with this problem of dissociation, but in turn can cause increased erosion (Antonson, 2007).

Magnetoplasmadynamic Thruster

In comparison to other EP systems, MPD thrusters have a relatively low efficiency rate. Like the other systems in this paper, the efficiency percentage of these systems is heavily reliant on the chosen propellant. MPD systems on the Japanese MS-T4 spacecraft were pulsed with the performance of 22% efficiency with ammonia and 70% efficiency with lithium (Myers, 1993). A study done by Myers included 8 MPD thruster configurations. Myers found that thrust efficiency and specific impulse increase with applied field strength, with cathode and anode radii influencing efficiency-specific impulse relationships. Anode power deposition is the largest efficiency loss in the tests, representing between 50% and 80% of input power (Myers, 1993). MPD systems can vary largely in overall efficiency which is illustrated in the graph of Figure 9b. The chosen propellant, applied field strength, cathode power, and anode power play immense roles in the efficiency of these thruster systems.

Gridded Ion Engine

GIEs produce some of the highest efficiency percentages out of any EP systems. GIEs yield approximately double the fuel efficiency of HETs. Because of this, GIEs yield far more significant savings in satellite mass and cost (Infed et al., 2017). GIEs can reach efficiency percentages of up to 70% ("Ion", 2001). GIEs are considered some of the world's most efficient forms of propulsion, which is supported by the specific impulse capability seen in Figure 10b.

Hall Effect Thruster

HET thrusters, while they typically have high thrust densities, also can achieve quite prosperous efficiency. HET efficiency percentage ranges depending on propellant and development, but these systems typically produce 40% to 50% efficiency (Tahara, 2001). While these efficiencies are less than other EP systems, the efficiency percentages still surpass chemical propulsion.

Cusped Field Thruster

CFT systems have, on average, a very beneficial efficiency percentage. These systems can range in overall efficiency like the other electrostatic engines above. But some CFTs have been reported to reach efficiency levels as high as 80% (Yeo et al., 2021). Which, when compared to other EP systems, is quite high. However, I find it difficult to determine whether this percentage is supported by Figure 12b considering the lack of reported Isp rates from CFT testing. Many factors contribute to overall system efficiency, the main being compactness. As explained above, downscaling the size of CFTs is possible, but leads to conduction problems and engine inefficiency.

Other factors may be explored in promoting engine efficiency. It was thought that the change in magnetic thickness, length, and number may lead to better performance measures. An experiment showed that changing the middle stage's channel design offered no increased thruster performance, but further experimentation with magnetic thickness in other CFT stages could yield a beneficial result (Yeo et al., 2021) Furthermore a study of a CFT with four magnets, instead of two or three, yielded a 10% increase in engine efficiency (Yeo et al., 2021). Overall, further system optimization can help with this loss of efficiency in future testing (Liu et al., 2016).

3.4 Statistical Analysis

Cold/Warm Gas

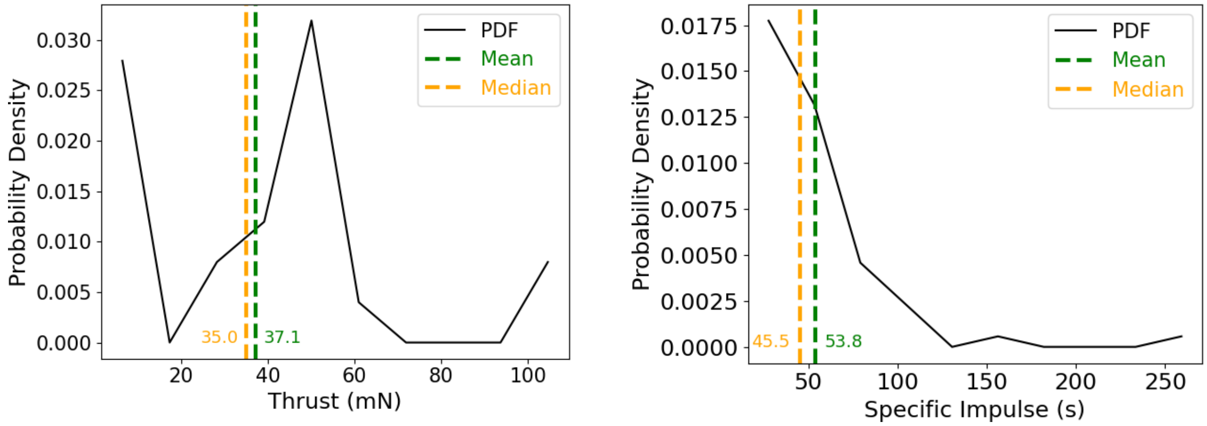


Figure 7a (left) and 7b (right): PDF of cold/warm gas thrust (left) and PDF of cold/warm gas specific impulse (right) with legend and overlay.

Resistojet

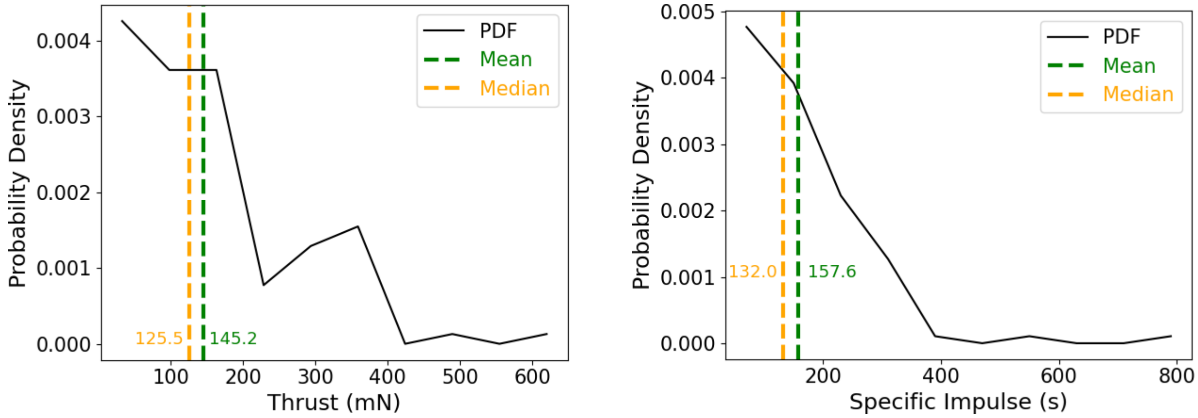


Figure 8a (left) and 8b (right): PDF of resistojet thrust (left) and PDF of resistojet specific impulse (right) with legend and overlay.

Magnetoplasmadynamic Thruster

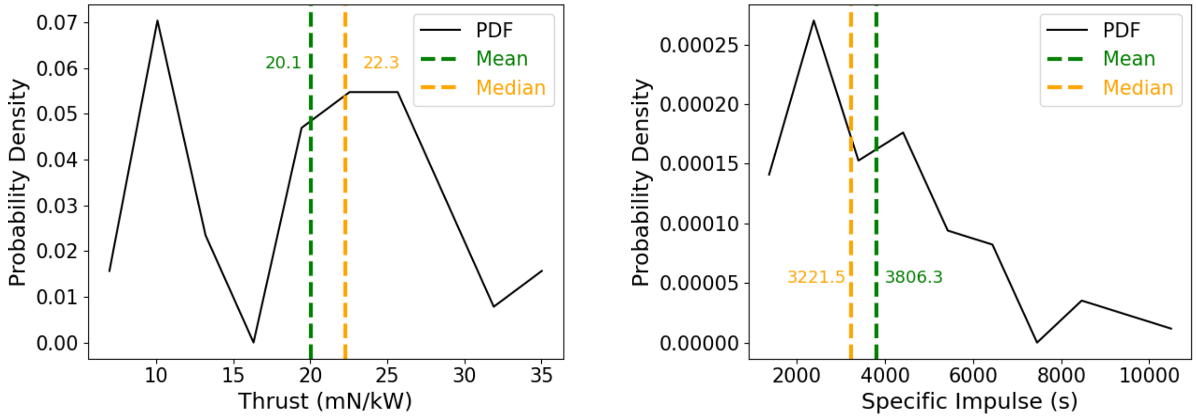
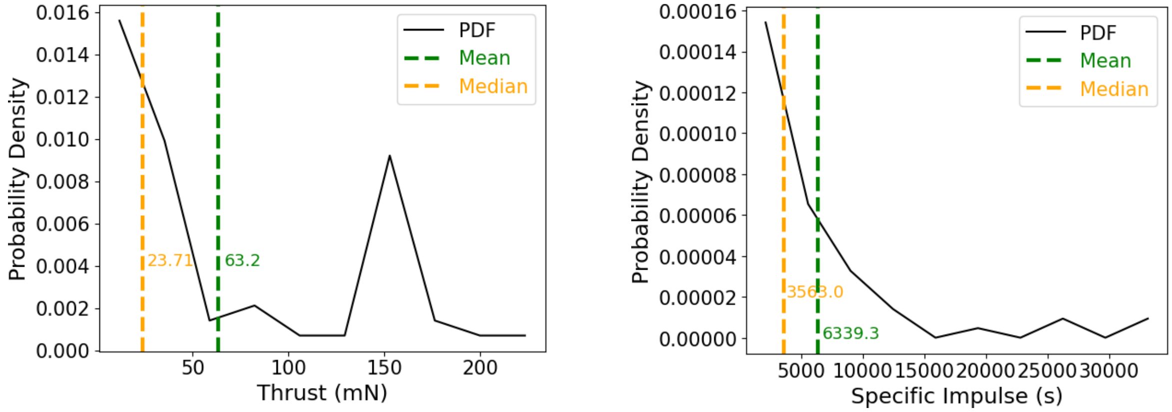


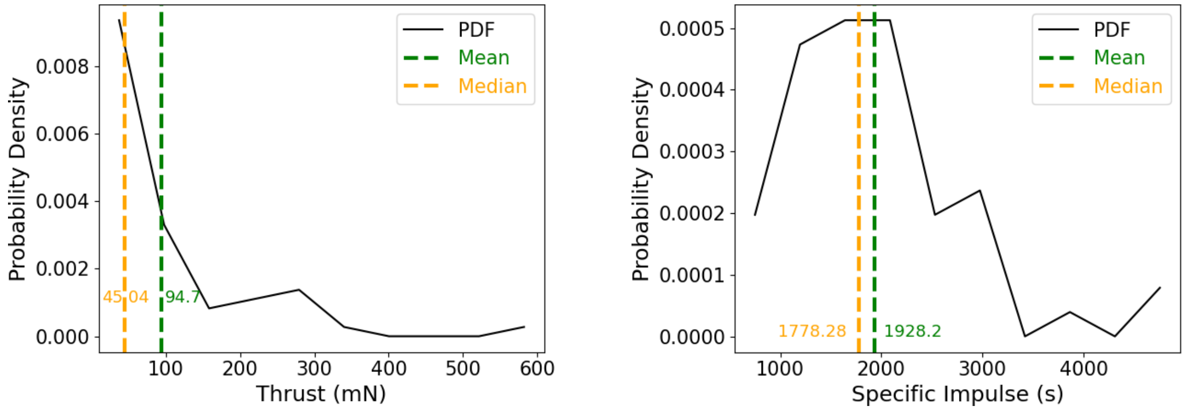
Figure 9a (left) and 9b (right): PDF of MPD thrust and PDF of MPD specific impulse with legend and overlay

Gridded Ion Engine



Figures 10a (left) and 10b (right): PDF of GIE thrust and PDF of GIE specific impulse with legend and overlay.

Hall Effect Thruster



Figures 11a (left) and 11b (right): PDF of HET thrust and PDF of HET specific impulse with legend and overlay.

Cusped Field Thruster

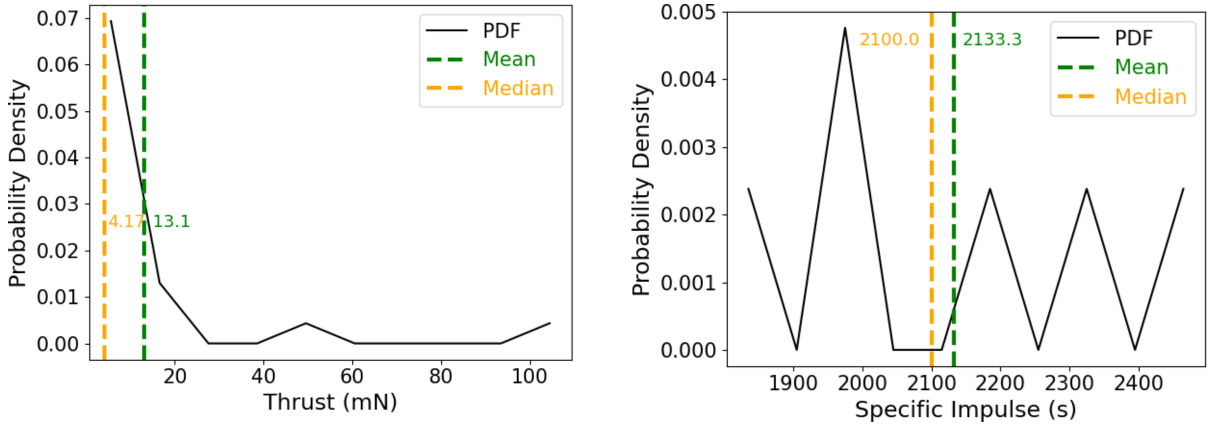


Figure 12a (left) and 12b (right): PDF of CFT thrust and CFT specific impulse with legend and overlay.

Tables and Bar Charts Comparing Thrust, Specific Impulse, and Range of Efficiency

Table 1: Thrust

Engine Type	**Mean (mN)**	**Median (mN)**
Cold & Warm Gas	37.1	35
Resistojet	145.2	125.5
Magnetoplasmadynamic Thruster	20.1 per kW	22.3 per kW
Gridded Ion Engine	63.2	23.71
Hall Effect Thruster	94.7	45.04
Cusped Field Thruster	13.1	4.17

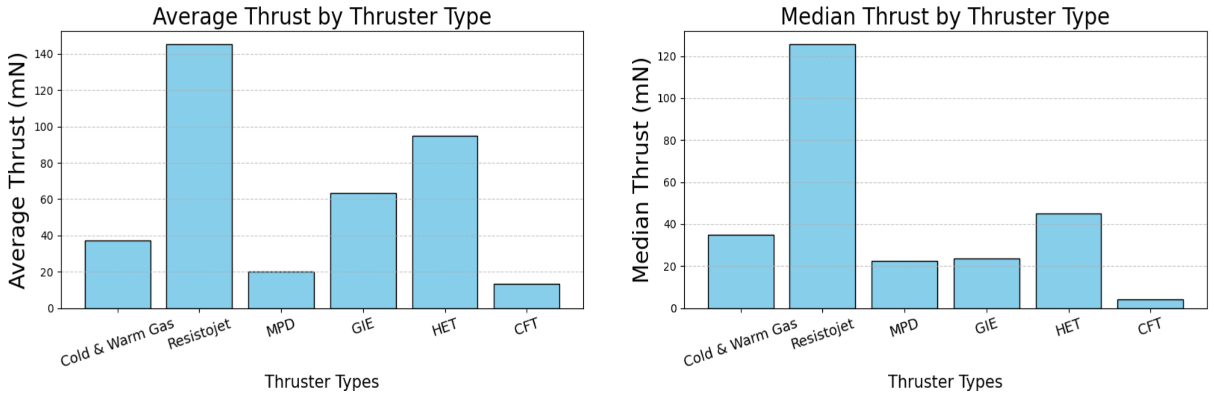


Figure 13a (left) and 13b (right): Bar charts of average and median thrust in milliNewtons of reviewed propulsion systems.

Table 2: Specific Impulse.

Engine Type	**Mean (s)**	**Median (s)**
Cold & Warm Gas	53.8	45.5
Resistojet	157.6	132
Magnetoplasmadynamic Thruster	3806.3	3221.5
Gridded Ion Engine	6339.3	3563.0
Hall Effect Thruster	1928.2	1778.28
Cusped Field Thruster	2133.3	2100.0

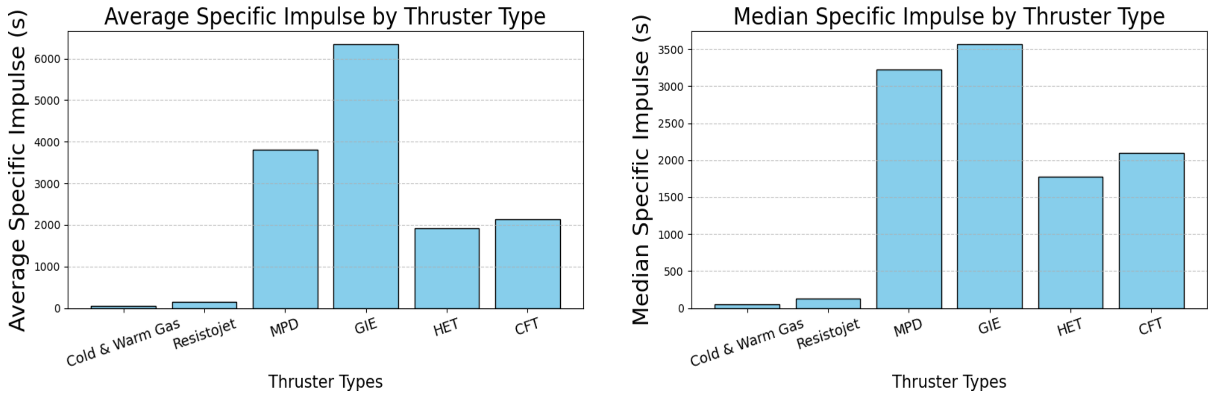


Figure 14a (left) and 14b (right): Bar charts of average and median specific impulse specific impulse in seconds of reviewed propulsion systems.

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3.5 Environmental Impact

Power Systems

Table 3. Efficiency.

Engine Type	Range of efficiency
Cold & Warm Gas	1% – 10%
Resistojet	65% – 85%
Magnetoplasmadynamic Thruster	40% – 60%
Gridded Ion Engine	≥ 70%
Hall Effect Thruster	40% – 50%
Cusped Field Thruster	≤ 80%

These electric propulsion devices can be powered in numerous ways, however, they are external sources, unlike chemical propulsion systems. One of the most notable being solar panels that take the energy produced by the sun and convert it to potential energy to later produce kinetic energy via the thruster system. These solar panels are an excellent source of green energy that provide numerous benefits like power ranging from 1-15 kiloWatts, and compatibility, which is illustrated by the numerous spacecrafts that have used them throughout history (Mazouffre, 2016). However, solar panels also have some drawbacks including lower efficiency percentages of 20% to 30%, high levels of degradation, which can be caused by numerous factors, and right now, is mainly bound to orbit around earth (Mazouffre, 2016). While it seems there are more disadvantages to using solar panels than benefits, it is imperative to consider their compatibility, history, and environmentally safe energy capture and output.

Another common form of powering EP is through the use of batteries. Batteries have evolved over time and depending on the type, some of environmentally safe while others are not. This is because some batteries are rechargeable and others are not, which creates waste both in space and on earth, increasing the carbon footprint of the aerospace industry. However, rechargeable batteries can have a very long lifetime as long as their range of operational temperature and overcharge tolerances are tended to. Batteries have many advantages like power outputs ranging from 0.1 kiloWatts to 100 kiloWatts, extremely high efficiencies that can surpass 90%, low levels of degradation, and they provide the ability of interplanetary orbit to EP systems (Mazouffre, 2016).

Overall, there are many ways to power EP systems, however, solar panels and batteries are two power sources that have important roles in environmental health. Firstly, solar panels are an great source of green energy, that rely on the infinite amount of solar rays produced by the sun. However, while they produce green energy, there is negative environmental impacts due to their production on earth and degradation while in space leading to increased carbon footprint and possible space debris. Second, batteries can be relatively safe for the environment. If they are rechargeable and kept in good condition they can be used for a long time and are extremely reliable. But, the production of the these batteries, along with the waste from their unrechargeable counterparts, creates waste and an increased carbon footprint for the aerospace industry.

EP System Emissions

EP spacecraft systems typically use an electric field or magnetic force to accelerate a propellant, which is typically a gas like the commonly used xenon. Because of this, these EP systems aren't capable of producing greenhouse gas emissions, unlike other chemical propulsion systems. Also, due to high efficiency percentages of these systems, less propellant and there is a greatly decreased flow rate compared to chemical systems (Crofton & Hain, 2007). While the propellants of these systems are safer, their costs, especially xenon's can be quite high, making them not as sustainable as suspected. Moreover, it's important to consider where the these systems are being used, mainly, outside or our atmosphere. Since this is the case, much of the used propellant is ejected into space and doesn't directly have an impact on our environment. But, let's not forget the way for these propulsion systems to get to space is via a rocket launch. The rockets that are needed to launch them into orbit still use chemical propulsion, which contribute to greenhouse gas emissions, soot, and other pollutants. Additionally, it's necessary to remember malfunctions happen. Malfunctions in spacecraft equipped with electric propulsion systems could contribute to the growing problem of orbital debris if the propulsion systems fails to deorbit a satellite properly.

However, while there isn't much to worry about considering emissions, in *Environmental Consideration for Xenon Electric Propusion*, it is made clear that plume concentration is greater near the thruster than natural abundance levels (Crofton & Hain, 2007). Additionally, compared to natural resources, the eroded particles from xenon propulsion have a fair amount of atmospheric mixing and transport, but are still considered to be quite insignificant. One of the main things that causes concern is problems relating to system erosion. Eroded particles may be expelled from the thruster and make its way into our environment (Crofton & Hain, 2007).

3.6 Trade-offs

Cold/Warm Gas

Advantages
- Simple design, low cost, and reliable.
- Immediate response and high precision for altitude control.

Disadvantages
- Low specific impulse.
- Low thrust (mN).
- Inefficient for large delta-v requirements due to high propellant consumption.

Applications
- Altitude control and station-keeping in small satellites.
- Short-duration missions or situations requiring simplicity.

Resistojet

Advantages
- Higher specific impulse (100-300s) compared to cold/warm gas thrusters.
- Simple and relatively low-cost technology.
- Can use non-toxic propellants like water or ammonia.

Disadvantages
- Quite limited efficiency compared to other electric propulsion systems.
- Requires onboard power to heat propellant.

Application
- Small satellite propulsion for altitude control and small orbital adjustments/maneuvers.

Magnetoplasmadynamic Thruster

Advantages
- High thrust-to-power ratio.
- High exhaust velocity.
- Efficient for high-power missions with substantial delta-v needs.

Disadvantages
- High power requirement (kW to MW range).
- Limited operational life due to electrode erosion.
- Complex thermal management.

Application
- Interplanetary missions requiring fast transit times.
- High thrust-cargo transportation in space.

Gridded Ion Engines

Advantages
- Extremely high specific impulse (1000-10,000s).
- Efficient propellant usage, especially for long-duration missions.
- Mature and well-understood technology.

Disadvantages
- Low thrust.
- Unsuitable for quick maneuvers.
- Requires substantial power and neutralizer for charge balance.
- Vulnerable to grid erosion.

Application
- Deep space exploration.
- Station-keeping for geostationary satellites.

Hall Effect Thruster

Advantages
- High specific impulse (1000-2500s).
- Moderate thrust.
- More robust and longer-lasting than GIEs.
- Efficient for station-keeping and orbit-raising.

Disadvantages
- Moderate power requirements.
- Lower efficiency than ion engines at high specific impulse.
- Magnetic field complexity increases costs and size.

Application
- Satellite station-keeping.
- Orbit transfers.
- Interplanetary missions.

Cusped Field Thruster

Advantages
- Reduce erosion compared to HETs.
- Potential for high thrust-to-power ratios and scalability.
- Efficient at high power ranges.

Disadvantages
- Emerging technology, less flight heritage.
- May require advanced materials and cooling systems.

Application
- Promising for next-generation interplanetary missions.
- High-power orbital transfer and deep-space propulsion.

4. Conclusion

Overall, EP systems outperform gas propulsion systems in the many categories of range in specific impulse, engine life, efficiency, and thrust. However, cold and warm gas propulsion is simpler than electric propulsion systems in design, manufacturing, and implementation, which makes them quite a cost-effective option when choosing a system for satellite-keeping and orbital control. All the EP systems in this paper seem to hold their own benefits and disadvantages when it comes to spacecraft application. Resistojets seem to be the better candidate for satellite propulsion while MPDs, GIEs, HETs, and CFTs all illustrate better opportunity for interplanetary or deep space exploration. But, based on the research presented, resistojets and Gridded Ion Engines seem to produce some of the best advantages in spacecraft implementation. Based on the probability density functions of thrust we can see resistojets can produce higher amounts of thrust in milliNewtons than other electromagnetic and electrostatic propulsion with an average of 145.2 mN. This thrust range can prove to be a better choice for satellite and space station propulsion than cold and warm gas systems. In regards to specific impulse, Gridded Ion Engines can produce the most in comparison to the other EP systems and the values soar over those achievable by cold and warm gas propulsion. Once again, specific impulse references the efficiency of an engine in terms of the amount of thrust generated per unit of propellant consumed. That said, GIEs being able to provide some of the highest specific impulse, with an average of 6339.3 seconds of Isp, gives the conclusion they have some of the best efficiency to thrust ratios of all of these systems. This is additionally supported by the fact their efficiency percentages can reach 70%. Therefore, someone considering the implementation of electric propulsion, may consider resistojets if they prioritize high thrust, and GIEs if they would rather prioritize high specific impulse and fuel efficiency. But, of course, each mission requires different specifications and parameters that need to be met.

Considering MPD thrusters, HETs, and CFTs for application, advancements in their technologies need to be made. MPDs need extremely high power input for their application, which is something that many spacecrafts just can’t provide. The advancement or development of new battery or solar panel power sources may provide MPD thrusters with the power sources they need for more future implementation in spacecraft systems. HETs need advancements in their erosion rates, which is what is causing limitations on lifespan for these thrusters. Additionally, compared to GIEs, HETs can't compete in the realm of specific impulse considering their average time of Isp is 1778.28, 1784.72s less than the average based on the PDF of GIEs. Finally, CFTs are a relatively new technology. Advancements in almost every category of these systems are needed for practical application due to their limited operational experience and scalability. However, CFTs are looking like a promising candidate for future spacecraft application and missions.

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